Auto-Gopher-II – An autonomous wireline rotary-hammer ultrasonic drill – test results

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ABSTRACT

In-situ exploration the solar system planetary bodies requires the ability to penetrate the subsurface for sample collection. One type of a sampling device used in past missions that is continually being developed is the drill. In these extraterrestrial applications, the drilling systems have mass, volume and energy consumption constraints that limit their depth of penetration. To address the related challenge, a deep drill, called Auto-Gopher II, is currently being developed as a joint effort between JPL's NDEAA laboratory and Honeybee Robotics Ltd. The Auto-Gopher II is a wireline rotary-hammer drill that combines breaking formations by hammering using a piezoelectric actuator and removing and collecting the cuttings by rotating a fluted bit. The hammering is produced by the Ultrasonic/Sonic Drill/Corer (USDC) mechanism that has been developed by the JPL team as an adaptable tool for many drilling and coring applications. The USDC uses an intermediate free-flying mass to convert high frequency vibrations of a piezoelectric transducer horn tip into lower frequency hammering of the drill bit. The USDC concept was used in a previous task to develop an Ultrasonic/Sonic Ice Gopher and then integrated into a rotary hammer device to develop the Auto-Gopher-I. The lessons learned from these developments were implemented into the development of the Auto-Gopher-II, an autonomous deep wireline drill with integrated cuttings management and drive electronics. Subsystems of this wireline drill were developed in parallel at JPL and Honeybee Robotics Ltd. In this paper, we present the latest developments including the integration of the whole drill, laboratory testing and field test results.

KEYWORDS: Planetary sampling, piezoelectric devices, wireline drill, life detection.

Introduction

One of the most pressing current questions in space science is whether life has ever arisen anywhere else in the universe. In addition to remote sensing, in the solar system we have the ability to send probes for in-situ sample acquisition and analysis. As water is a critical prerequisite for all life-as-we-know-it, NASA prioritizes future exploration targets that are currently known to have or have had in its past copious amounts of liquid water. In the latest Planetary Decadal Survey [Vision and Voyages for Planetary Science in the Decade 2013-2022], three bodies Mars, Europa, and Enceladus were specifically called out for future exploration because of the accessibility of aqueous regions. Each of these planetary bodies have had the surface altered more or less depending on the local environmental conditions. In the Martian past, liquid water was ample on the surface, and was lost to space. The current rocky and dry surface is exposed to intense UV, solar and cosmic radiation that creates an oxidizing layer that destroys fragile biosignatures in the form of organics on the surface [Navarro-Gonzalez, 2006; Hecht, 2009]. On other bodies, the solar and cosmic radiation fluxes can be even stronger, especially in the ice covered surface that currently exists. Radiation from Jupiter can destroy molecules on Europa's surface. Material from Europa's ocean that ends up on the surface will be bombarded by radiation, possibly destroying any biosignatures, or chemical signs that could imply the presence of life [Nordheim, 2018]. At the same time the habitability can be sustained by radioactive energy provided by natural unstable isotopes [Altair, 2018]. On the surface of Enceladus where material is ejected into space from geysers in the South Polar Region, much of that material falls back onto the planet and forms fresh surfaces [Hansen, 2006, 2011]. This fresh material on the Enceladus surface may be the material that would present the highest sampling interest. These bodies have the highest likelihood of finding either extant or extinct life in the solar system, but all require a sample acquisition strategy. A drill sampling system is required to penetrate the subsurface of the explored bodies, capture samples for analysis, and present the unaltered sample to instruments for analysis. While it is obvious that there is a need to access the subsurface on planetary bodies, the actual act of drilling on extraterrestrial bodies is very challenging.

With the development of Auto-Gopher, we demonstrated a scalable technology that will make deep drilling possible in the next 2 decades with current launch vehicles, power sources, and entry descent and landing (EDL) systems. It utilizes a wireline approach similar to the one used in Antarctica and has the potential to capture ice cores from kilometers depth. The technology and concept of operation has been developed in conjunction with future mission constraints including mass, power and operation effectiveness.

In the reported wireline approach, the drill is essentially a tube that encompasses the coring bit, mechanisms and actuators. The drill is suspended at the end of a light weight tether and in turn, penetration depth is limited only by packaging capability of the tether. This enables drilling to 10 m or 100 m or up to 1 km, without significant increase in system mass or complexity.

The obvious limitation with drilling is available power. Proven power sources for landed missions are solar panels and Radioisotope Thermal Generators (RTG). In order for the Auto-Gopher-2 to drill through ice it needs a few 100 Watt of power [Bar-Cohen, 2014; Badescu, 2013]. This is very feasible with the current MSL power system resulting in ability of drilling for 10% to 30% of the operational time. In contrast, an ice melt probe, needs kWs of power and this requires development of small, space-worthy nuclear reactor, something that is still constrained by technology development and politics for the near future.

A major concern in terrestrial wireline drilling is a borehole collapse. The hole cannot only collapse above the drill trapping the drill below the collapse point, but also the hole can get smaller through creep, and pinch the drill at a choke point. For ice drilling, this is not an issue as ice creep is a function of ice temperature, pressure at depth and gravity. The low gravity and ice temperatures on bodies such as Mars and Enceladus is much lower than ice temperature in Antarctica, and is expected to keep the creep to a minimum. The Auto-Gopher is periodically retracted out of the hole to extract the drill cuttings. During these up and down trips, the drill could engage counter rotating reamers to keep the borehole open, if needed.

In a previous research task completed in 2012, the Auto-Gopher-1 wireline drill was developed and advanced to TRL 4 and it was demonstrated to perform semi-autonomous coring in a 40 MPa gypsum to a depth of 3 meters, which is 1.5X the drill's length. Building on this promising technology, we developed in a follow-on task a fully autonomous Auto-Gopher-2 (AG-2) wireline system (Figure 1). After successful tests in the lab at Honeybee Robotics, the drill was field tested in a 40 MPa gypsum (at US Gypsum quarry) and reached 7.52 meters deep reaching greater than 2x of the drill length as originally proposed. In this paper, we present the latest developments including the integration of the whole drill, laboratory testing and field test results.

Figure 1: Auto-Gopher II in the field test deployment.

Transducer development (assembly, laboratory testing, integration)

The selection of the piezoelectric transducer size was determined by the size of the drill bit and the need to simplify the electric driver. Two sets of piezoelectric actuators with 5.2 kHz resonant frequency were fabricated and tested; one used 5.1mm thick PZT rings and a second one used 6.35mm thick PZT rings. Both sets used the same rings outer diameter of 50.8mm. The larger thickness PZT rings were selected to accommodate the voltage supplied by the system without the need to use an intermediate transformer. A series of piezoelectric actuators with 6.35mm thick rings and alumina insulating rings at both ends of the stack were analyzed, fabricated, and tested in the lab prior to integration into the drill system. Two of the actuators that were used as backup for the field trip are shown in Figure 24. The geometry of the backing and horn were modified to include flat sections to interface with wrenches in the assembly process. Epoxy has been used to compensate for any surface mismatches between ceramic rings, electrodes, and backing and horn. In addition, 3D printed support fixtures were fabricated to maintain electrodes alignment during the stress bolt preloading. These steps have been found useful in assembling the piezoelectric actuators.

Figure 2: Spare transducers fabricated with 6.35mm thick PZTs and alumina insulation rings

Figure 3 shows electrical impedance and phase spectra of the 5.2 kHz piezoelectric actuator, where the resonant, anti-resonant frequency and electromechanical coupling factor of the actuator are found to be 5.19 kHz, 5.299 kHz and 0.19, respectively. The corresponding impedance at resonant and anti-resonant frequency are found to be 10 Ohm and 22.26 kOhm.

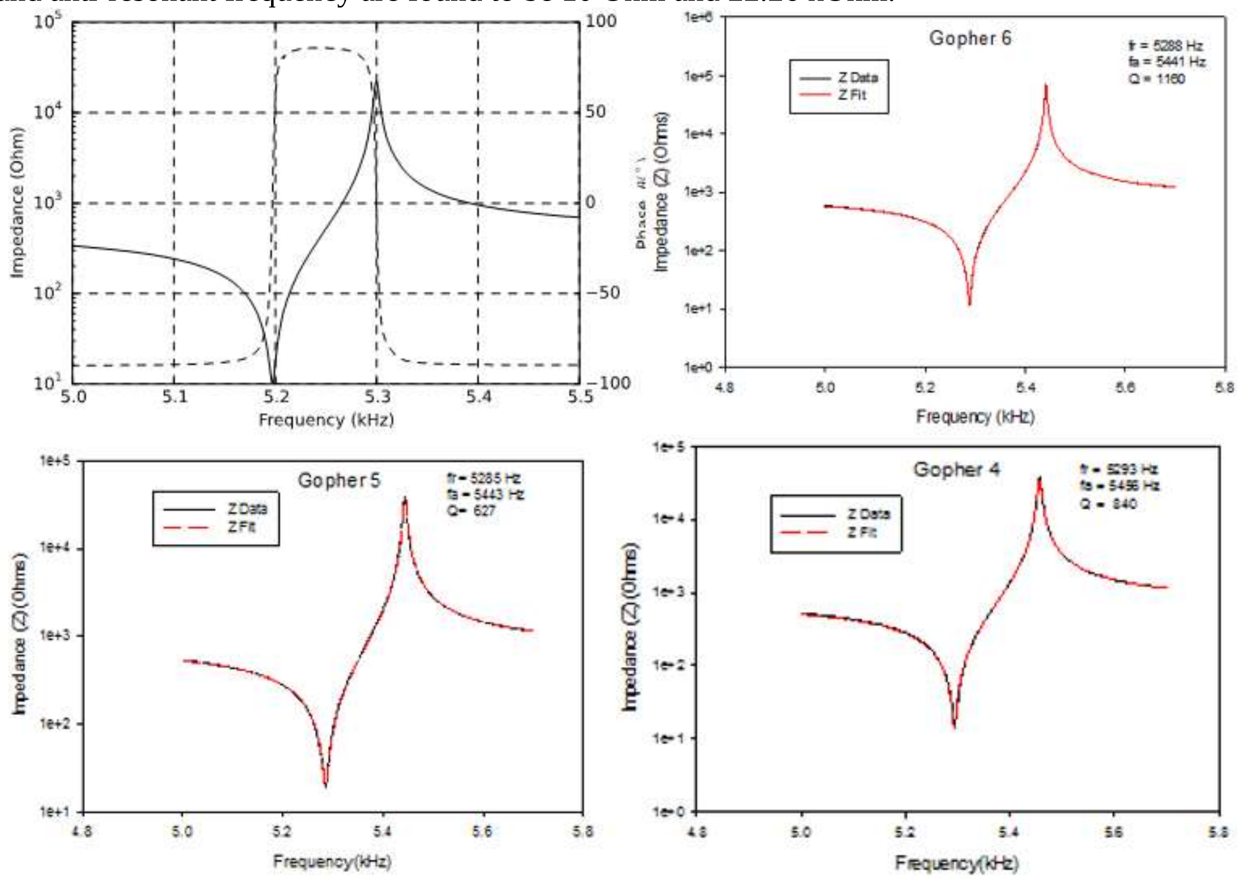

Figure 3: Electrical impedance and phase data for the 5.2 kHz piezoelectric actuator.

Drive electronics and Control Software for Ultrasonic Hammer

The drive electronics was developed to fit inside the tube of the Auto-Gopher-2 system. The control software monitors the current and the frequency relative to the resonant device. The drive electronic development efforts were undertaken to develop an optimal combination of hardware and control software. This approach accounted for small changes in the resonance frequency caused by environmental changes in temperature, pressure, and mechanical boundary conditions. The software monitors the power in real time allowing for adjustment to the frequency to maintain the proper phase offset and current to the horn.

The fixed large input voltage coming into the piezo drive electronics presented a couple challenges to overcome. The impedance of the piezo actuator at resonance is ~34 Ohms - if driven at resonance, with a fixed voltage of 280V, would result in 2.3kW of power delivered to the system. In order to properly control the power delivered to the actuator, the piezo is driven off resonance between the resonance and anti-resonance frequency where the impedance is larger. Figure 27 shows the bode plot of the current as a function of frequency. We have chosen the area of operation above the resonant peak for hardware safety reasons and stability of the impedance.

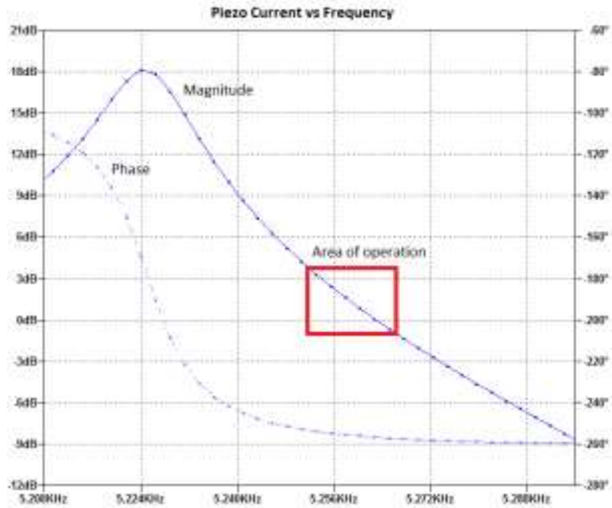

Figure 4 Plot of piezo current vs frequency (0dB is 1A current).

Driving off resonance introduces a few subtleties into the reported power measurement due to the phase angle between the current and voltage. Given that the voltage and current are out of phase this means there are times where the voltage will be positive, but the current is negative, or vice versa, which results in negative power flowing "into" the actuator. This is due to energy being stored in the mechanical system of the piezo and then delivered back into the drive electronics. Measuring just the piezo current would tell us the horn velocity and apparent power but would not detail the real power delivered to the actuator/drill/rock. Therefore, we have two current measurements in the drive electronics, a low side current sense resistor where the average of the current can be used to infer the real power delivered to the actuator/drill/rock and a hall current sensor for monitoring the piezo RMS current to control horn tip velocity.

Looking to the future, implementing an efficient buck voltage converter to adjust the input voltage would be very beneficial. The actuator could operate at resonance, apparent power would equal real power delivered, and no current would flow back into the drive electronics.

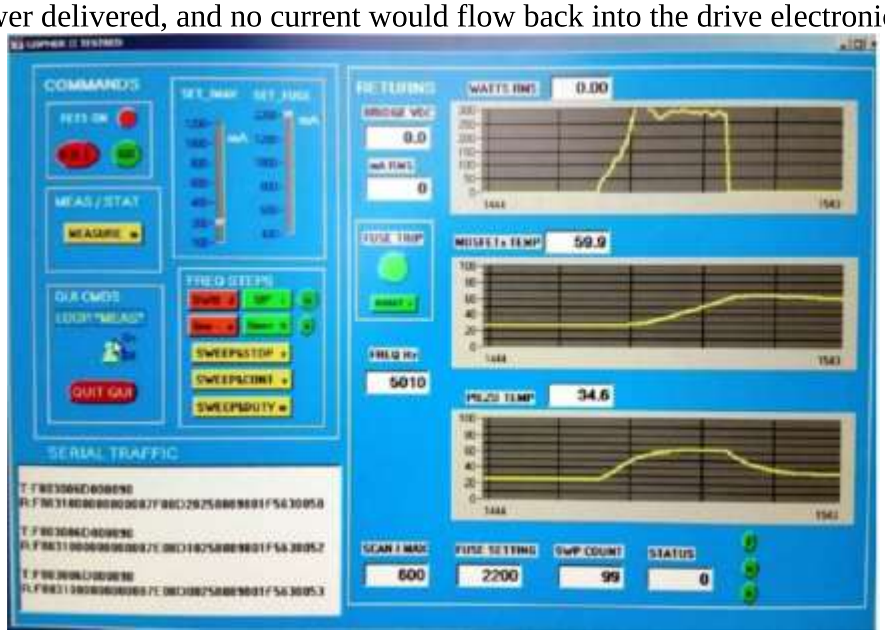

Figure 5: C++ Lab GUI displaying MODBUS Serial traffic after 300W RMS run. MOSFETs ran without heat sinking to test worst-case conditions.

The developed driver has been used for dozens of actuator tests at powers up to 300W RMS (Figure 5). Some anomalies in the output current wave shapes were investigated leading to part change-outs, like the MOSFETs and bias components. After significant testing and adjustments, the electronics was found to be operating with design specifications. Due to the large input voltage to the drive electronics a second driver PCB was populated, programmed and calibrated for MODBUS software design use at JPL. A high voltage opto-isolated relay, was packaged in the PCB enclosure, and modified for slow turn-on to prevent unwanted current surges.

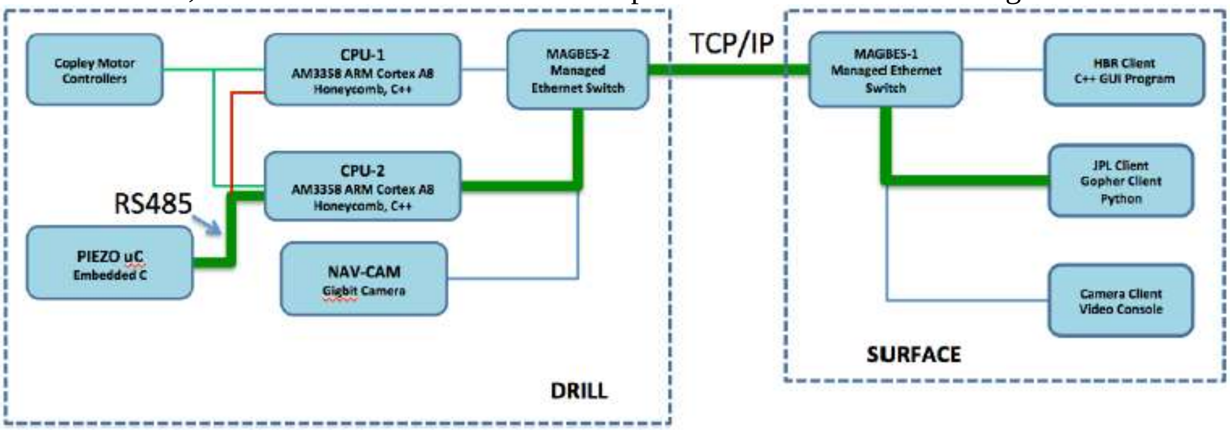

Figure 6: Communication Overview, successful communication from surface client to drill piezoelectric driver.

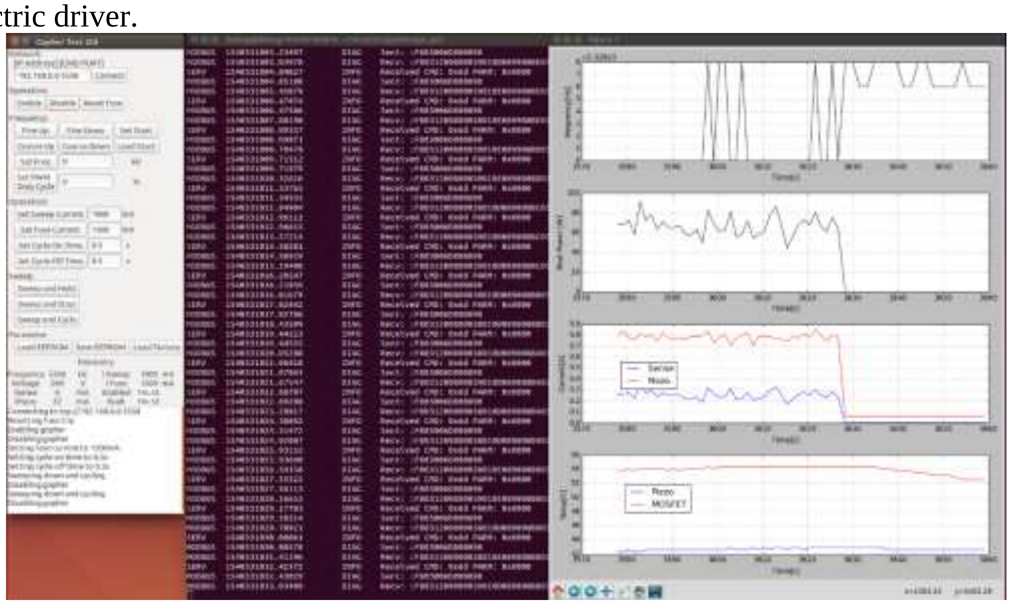

Figure 7: Surface side GUI showing command GUI and real time telemetry plotting

A communication overview schematic is shown in Figure 6 for the Auto-Gopher II command and control. Successful communication from the JPL client to the embedded piezoelectric microcontroller using the TCP/IP to RS485 interface was accomplished. The JPL client is a GIMP Toolkit Graphical User Interface (GUI) utilizing a gopher library that was written in Python to allow easy portability and platform independence. The python library uses the ZeroMQ messaging protocol to communicate with the gopher server located in the drill using TCP/IP commands. The gopher server located on the AM3358 platform inside the drill communicates over two ports including a subscriber based model on one port, and a request and reply model on the second port. The publisher broadcasts the event records of commands received, Modbus communication, and other diagnostic information to clients that have subscribed to the server. This allows status to be broadcast across multiple devices, where the failure of one client does not take down the remaining subscribers. The request and reply portion of the server receives commands from a client, executes the command, and replies with the result of that command. Figure 7 shows the GUI used to monitor and control the running parameters of the piezoelectric actuator in parallel to the control of the drill system.

Laboratory testing

Laboratory tests of the integrated drill (Figure 8) were conducted at Honeybee by following the same steps as during system level testing of the Auto-Gopher-1 drill. In particular, the drill was placed above a block of 40 MPa Indiana Limestone. The Indiana Limestone was chosen for several reasons:

1. It is homogenous, uniform rock and hence any abnormal drill operations would be attributed to the drill itself and not potential changes in rock properties.
2. Its strength is similar to gypsum at the US gypsum quarry, the selected field test site.
3. Its strength is similar to ice at cryogenic temperature.

A softer rock, Cordoba Crème Limestone, was used to check and tune the drilling control loops. This involved adjusting the set variables and gains for both WOB and auger torque which are used to control the output ROP (by the z-stage). For drilling in harder rock, a higher WOB value is usually set. The power output of the drill can be limited by adjusting the set auger torque while the auger rotates at a constant 100 rpm. Maximum torque output is 60 Nm of which approximately 10 - 15 Nm is used to overcome internal friction in the auger drive.

Once the software control loops were tuned, tests were completed to assess the performance of the drill in both rotary-only and rotary-hammer mode in both rock strengths that were selected.

Figure 8: Auto-Gopher II lab testing.

The controlled test results obtained in the lab drilling 45 MPa Indiana Limestone have shown that compared to drilling with rotation only, when augmenting with the piezo-actuation at 100%

duty cycle resulted in a 30% increase in rate of penetration (ROP) from 0.16 to 0.21 mm/s. In addition, when the piezo-actuation was activated there was also a decrease in the specific energy from 712 to 614 Wh/m. This controlled test reflected the closest to drilling 40 MPa gypsum. However, when drilling the softer 25 MPa Cordova Creme there was observed only slight improvement in the ROP and no advantage in specific energy. A possible explanation is that for softer rocks, higher WOB and fixed RPM the cuttings carrying capability of the bit flutes is reached and adding hammering does not increase the drill penetration rate.

Field Test results

To validate the deep drilling capabilities, the drill was tasked to reach the depth of 5 m or 2x the drills length, whichever is greater. The tests were highly successful and everything worked well reaching 7.52 meter deep (Figure 9). This depth was sufficient to demonstrate the deep drilling capabilities of the Auto-Gopher II system. The field tests took place at the US Gypsum Company gypsum quarry outside Borrego Springs, CA. The Borrego Spring site was chosen because it was also the site of the Auto-Gopher I tests and hence we were familiar with the logistics. US Gypsum Inc. performed Unconfined Compressive Stress tests on three gypsum cores and measured the strength of 38 MPa ±2 MPa, which is in the range of ice at cryogenic temperature. The reasons for field testing as opposed to lab testing are numerous, but the major ones include:

1. It is expensive to set up a 4-6 m column of rock and brace it to prevent collapse during earthquake (California rules), and add scaffolding for placing a >2 m drill on top. It is less expensive to rent a truck, pack up the gear and drive 3 hours to the field site.
2. It is impossible to introduce geological uncertainty in a lab. Field offers geological uncertainty and, in turn, it is a better location for testing robustness of the drill to changing conditions. For example, in the laboratory tests all rock blocks are without cracks or voids. In the field, a large rock crack or void presents the risk of creating pebbles large enough to jam the drill bit. Designing the drill control software to monitor for sudden increases in the bit drive torque helps mitigate these possible problems.
3. There is also an inherit risk to conducting tests in a field that makes decision making more conservative and in turn more as if it was a real mission. If a drill gets stuck in the field, it will most likely remain there forever or it will take considerable effort to pull it out. In a lab, if a drill is stuck, it will be relatively easy to break the rock and free the drill.

Figure 9: The field test of the Auto-Gopher II.

Figure 10 shows a few images from the field test with the full drill into the drilled hole (left) drill operation during the day (middle) and at night (right).

The transducer software control parameters were set to: Sweep Current 1000mA; Fuse Current 1500mA; Cycle Time ON 2 sec; Cycle Time OFF 1 sec (Duty Cycle 66%).

The monitoring of the piezo-actuator and the MOSFET temperature was accomplished in the graphic user interface of the control software. The results showed: piezo temp starts at ~25°C in the morning and reached up to 70°C by the end of day; It does not cool to the starting temperature if the drilling cycles are about 20 min apart with a current at 0.6 – 1.0A;

Figure 10 Field test with the drill fully inside the drilled hole (left), drilling operations during the day (middle) and night (right)

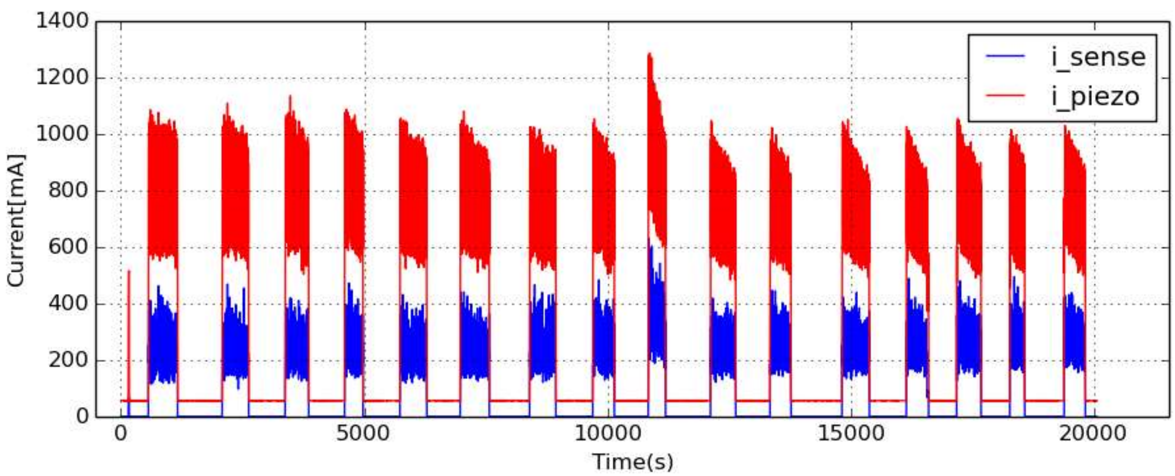

Figure 11: The current recorded during the drilling. The current was sampled at 1Hz. The average piezo current during drilling is approximately 0.850A. The average real transducer power delivered is 68W

Figure 11 shows the current across the transducer (i_piezo) and from the bus DC power (i_sense). Given the fact that the transducer is not driven at resonance there is a phase difference between the AC current and transducer drive voltage resulting in an average transduce power of 68W.

The temperature increases during drilling and decreases during the transducer time OFF (retracting the drilling, cleaning the bit and redeploying the drill into the hole). With each drilling cycle, the transducer reaches a higher and higher temperature until it reaches approximately 70 °C and then stabilizes. The Curie temperature (>300 ^{o}C) of the piezoelectric rings used allows the transducer operation at this temperature.

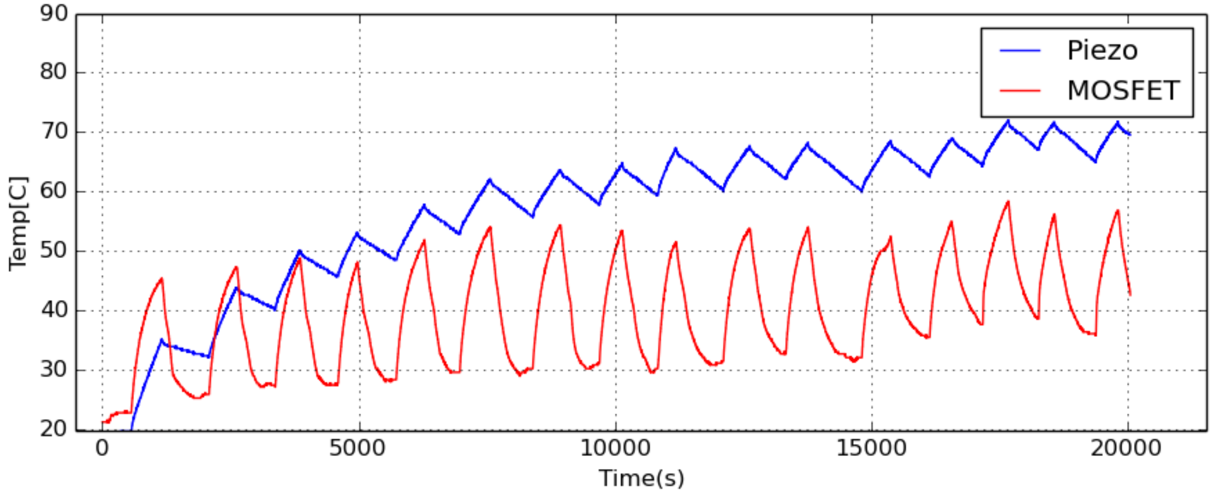

Figure 12 The transducer and MOSFET temperature monitoring during the day.

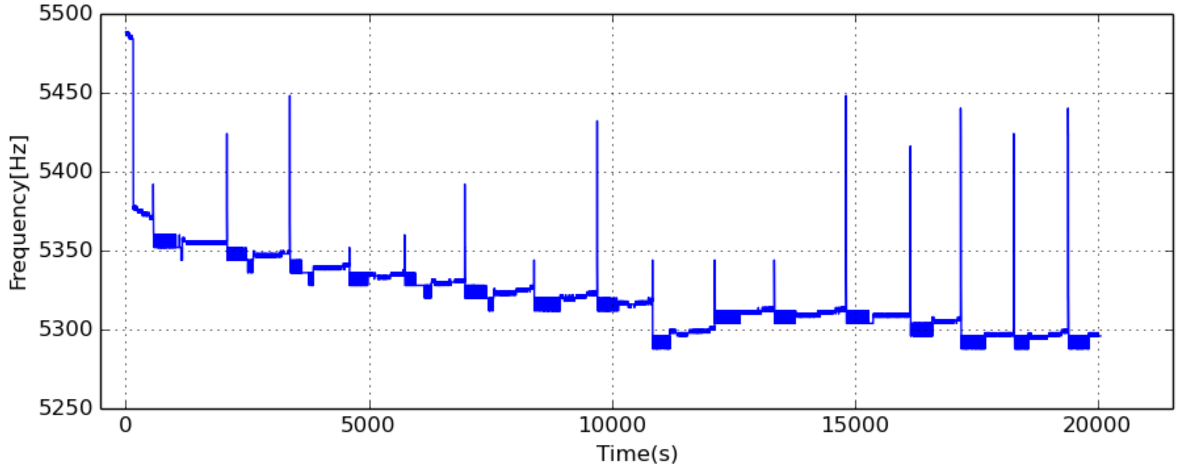

Figure 13: Transducer control frequency recorded during day 1

As the transducer's temperature increases, the drive frequency shifts lower from a start of 5350Hz to 5300Hz when the transducer reaches 65°C. Frequency sweep is performed at the beginning of each drilling cycle.

Conclusions and Future work

In this paper, we presented the latest results in the development of the piezoelectric transducer for the Auto-Gopher II, including the piezoelectric hammering transducer, the drive electronics, integration into a rotary-hammer drill system and laboratory and field test results.

A 5.2 kHz transducer was designed, parts were fabricated and assembled and preliminary tested using lab drive electronics and task developed drive electronics and control software. Drive electronics and control and communication software for driving the transducer and exchange information with the rest of the drill system were developed and integrated in the Honeybee Robotics developed drill system.

With the development of Auto-Gopher II, we demonstrated a scalable technology that will make deep drilling possible in the next 2 decades with current launch vehicles, power sources, and entry descent and landing (EDL) systems. The mass, size and power requirements can be derived from the MSL size rover. The Auto-Gopher II requires < 500 W power and has a mass of 65 kg which means it would likely meet mission mass and power requirements. However, the size, especially length, would need to be reduced. It is currently 3.7 m (3.2 without auger) and should be closer to 2 – 2.5 m in length. This is feasible considering that most of the electronics are off-the-shelf products. In addition, some components already have flight heritage, such as, for example, the Vectran© strength member in the umbilical cable, which was used to lower Curiosity on to the surface of Mars with the SkyCrane.

Acknowledgements

Research reported in this paper was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, jointly with Honeybee Robotics under a contract with National Aeronautics Space Administration (NASA). This research was funded by the NASA's MatISSE (Maturation of Instruments for Solar System Exploration) program.

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